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Bioelectricity generation from human urine and simultaneous nutrient recovery: Role of Microbial Fuel Cells

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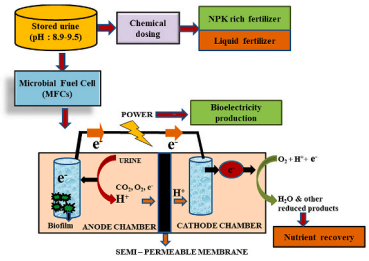
HIGHLIGHTS

- Human urine is a valuable waste rich in several key nutrients.
- Resource recovery from urine is gaining increasing attention.
- Microbial fuel cells provide an alternative and novel route to valorize urine.
- Simultaneous electricity generation and resource recovery from urine in MFCs.
- Further scale-up efforts are needed to bring this technology from lab to market.

GRAPHICAL ABSTRACT



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ABSTRACT

Urine is a 'valuable waste' that can be exploited to generate bioelectricity and recover key nutrients for producing NPK-rich biofertilizers. In recent times, improved and innovative waste management technologies have emerged to manage the rapidly increasing environmental pollution and to accomplish the goal of sustainable development. Microbial fuel cells (MFCs) have attracted the attention of environmentalists worldwide to treat human urine and produce power through bioelectrochemical reactions in presence of electroactive bacteria growing on the anode. The bacteria break down the complex organic matter present in urine into simpler compounds and release the electrons which flow through an external circuit generating current at the cathode. Many other useful products are harvested at the end of the process. So, in this review, an attempt has been made to synthesize the information on MFCs fuelled with urine to generate bioelectricity and recover value-added resources (nutrients), and their modifications to enhance productivity. Moreover, configuration and mode of system operation, and factors enhancing the performance of MFCs have been also presented.

1. Introduction

A human being produces approximately 2.5 L of urine in a day which is usually flushed down the toilet (You et al., 2016). Urine has high ionic strength ranging between 0.3 and 0.6 mol L^{-1}, and good content of calcium, urea, sodium chloride, nitrogen, phosphorous, potassium, and phosphate (Simha and Ganesapillai, 2017). It is identified as a 'useful waste' and in the past decade has become an attractive topic for research like wastewater treatment, waste management, and waste reclamation. To extract value out of the waste, modified waste management strategies create new prospects for wide-scale use of urine as fuel in bio-electrochemical systems (BESs) with simultaneous recovery of multiple

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resources and electricity production (Spangberg et al., 2014; Chipako and Randall, 2020). BESs are the trending water-energy nexus technologies that are focused on liquid treatment, resource recovery, and electricity production simultaneously (Colombo et al., 2017; Santoro et al., 2020). The basic working concept of all these treatment systems is the presence of anode-respiring bacteria that form a biofilm on the anode, and release electrons and protons during the breakdown of organic components of the liquid (Kumar et al., 2017a,b), followed by the movement of electrons to the external circuit to generate electricity (Santoro et al., 2017; Chen et al., 2019; Sharma et al., 2022).

Among BESs, MFCs are attracting more and more contemplation of the scientists ascribed to their unique characteristics and promising approach of converting the diversity of organic compounds into something resourceful (Rahimnejad et al., 2015; Pandey et al., 2016; Santoro et al., 2017). MFC concept was first used by botanist Michael C. Potter in 1911 to generate electricity using *Escherichia coli*, at the University of Durham, UK (Pant et al., 2012). In the MFCs treating urine, the organic components are oxidized in an anodic chamber, a bio-electrochemical redox reaction is completed at the cathode with the reduction of an oxidant (Ledezma et al., 2015; Santoro et al., 2019) and production of catholyte in the cathodic chamber (Gajda et al., 2016; Merino-jimenez et al., 2021). Additionally, a good amount of nutrients like N, P, and K are recovered at the end of the process (Chipako and Randall, 2020). Urine-derived fertilizers are rich in N, P, and K. Though, P:N and K:N values are low in urine, but ionic phosphates and potassium compounds can readily dissolve in water and become easily available to plant (Simha and Ganesapillai, 2017; Freguia et al., 2019). Bio-bricks can be manufactured from urine when disintegrated (under the action of urease-producing bacteria) carbonate ions from urea combine with free calcium ions to form calcium carbonate. Particles of calcium carbonate cement with loose sand particles and form a bio-brick (Lambert and Randall, 2019). Moreover, many pollutants can be removed simultaneously while treated collectively in a single MFC. For instance, high current density and high removal of Cr(VI) can be obtained in urine/Cr (VI) fuel cell in which urine is oxidized on carbon-based nano-Ni catalyst at anode and Cr(VI) is reduced at the catalyst-free cathode (Xu et al., 2016). Hence, using one waste (human urine), another waste (Cr(VI)) can be treated.

Various wastewater sources had been used as a substrate to generate bioelectricity using MFCs. The most popular substrates are municipal, agro-processing, dairy, food processing, paper recycling, beverage, refinery, winery and distillery wastewater, human urine (Pandey et al., 2016; Shahid et al., 2021). Urine is a comparatively important waste because it is a rich source of NPK, and many other macro and micronutrients. Because of the shortage of organic raw materials, and the adverse effects of chemical fertilizers in agriculture, the application of ecologically safe human urine has been gaining popularity as a fertilizer for agricultural practices. Urine is an abundant waste product and it has already been reported as an excellent fuel for generating electricity in MFCs. Though wastes like wheat straw effluent, rice straw hydrolysate, corn stover, vegetable waste extract, cattle manure, and manure wash wastewater are considered as good substrates for power generation, the majority of other wastewater sources including poultry and swine waste; plant and yard waste, fruit and cassava processing effluent; chicken manure, brewery, dairy wastewater show poor performance for bioelectricity production in MFCs (Pandit et al., 2021). Moreover, such substrates produce end products that further create disposal issues. Human urine has been studied as a favorable substrate for high power output in MFCs, generates many essential nutrients during treatment, and does not produce substantial by-products at the end of treatment processes. Therefore, urine has been found better over other wastewater sources for power generation in MFCs.

The field of resource recovery from urine has seen tremendous growth in recent years and BES is an important approach in this regard. The research on using BES/MFCs for urine treatment and resource recovery has seen several new aspects being reported in recent years. While some reviews on this subject already exist, it is worthwhile to mention here that we report in our review the most recent updates and link them to previous research efforts, and therefore it is different from the previously published review articles. The review includes an insightful discussion on the composition and characteristics of human urine, configuration and types of urine-fed MFCs, mode of MFC operation for power generation from human urine, and application of MFCs to recover useful nutrients from the waste. Additionally, technologies other than MFCs to recover value-added products from urine are conversed. Modifications in MFCs to enhance their performance, and factors affecting their performance are discussed. In this article, recent research reports are coalesced to emphasize the role of MFCs to use urine for power production and reclamation of value-added products. This novel article critically synthesizes state-of-the-art advancements in the use of MFCs in extracting resources and generating electricity from the valuable waste 'human urine'. The study is significant in terms that it provides readers an insight for a shift towards abundantly available waste i.e., human urine which creates subsequent opportunities for large-scale recovery of multiple resources, and bioelectricity production with few design guidelines. Moreover, urine treatment does not generate harmful end-products at the end of treatment processes that cause environmental effects. Therefore, urine is a good choice for generating something useful out of waste.

2. Human urine-the liquid gold of wastewater

Urine is a 'valuable waste'. The estimated global production of urine is 1.16–1.54 $\times$ 10^{10} L per day which equates to approximately 1.5–2 L per individual and 4.22–5.62 $\times$ 10^{12} L a year. Urine mainly consists of 93–96% water, and only 5% as inorganic and organic compounds, salts, and soluble wastes of the human body like creatinine, urea, uric acid, amino acids, dissolved ions as chloride and sodium (Karak and Bhattacharyya, 2011). Urine contains 4.7–10.4 g L^{-1} dry matter with a solid loading rate of 57–64 g cap^{-1} d^{-1} and a COD level of 8–17 g L^{-1} (Rose et al., 2015; Santoro et al., 2020). The urine stream contains 75% of total N and 50% of total P present in domestic wastewater. However, it forms only 1% of domestic wastewater (Barbosa et al., 2019). So, it is worthy to note that how useful this waste is. It is rightly called 'the liquid gold of wastewater' (Randall and Naidoo, 2018).

2.1. Composition and characteristics of human urine

The complex composition of human urine contains many compounds in different concentrations which varies depending upon the difference in physical exertion, environmental conditions (like temperature, altitude, humidity, seasons), and diet (water, salt, protein intakes) (Adamsson, 2000; Karak and Bhattacharyya, 2011).

2.1.1. Composition of human urine

Water, salts, electrolytes, and ions form the major components of urine. Water is the major component that accounts for about 93–96% (Santoro et al., 2020). Urine contains about 4% urea and 2% other products including uric acid, creatinine, electrolytes, salts. The standard blood urea [$CO(NH_2)_2$] level is 20–40 mg L^{-1}, of which 30 g is excreted daily. The recommended level of uric acid ($C_5H_4N_4O_3$) is 2–6 mg L^{-1}, of which 1.5–2 g is excreted. Creatinine ($C_4H_7N_3O$) is the metabolic waste of creatin muscle forming 1.4–1.9 g $cap^{-1}day^{-1}$ of excretions and forms 0.670 g L^{-1} - 2.15 g L^{-1} of urine. Urobilinogen (UBG) is produced from bilirubin in the small intestine and can be oxidized to urobilin in urine (Hajra and Chowdhury, 2014). Other minor organic components are carbohydrates, pigments, fatty acids, mucin, enzymes, hormones, indican, and ketones.

Sodium chloride is the main inorganic salt or electrolyte responsible for maintaining electrolytic balance. Ions like potassium, calcium, magnesium are usually present as salts of chlorides, sulfates, and phosphates. Phosphorous is usually present as phosphates with varying

concentrations of 0.2 g L^{-1} - 2.5 g L^{-1} (Rose et al., 2015), potassium ranges between 0.4 g L^{-1} - 2.6 g L^{-1}, and for calcium concentration range is 0.03 g L^{-1} - 0.23 g L^{-1}. Ammonium ions are formed by the catabolism of protein and glutamine, which usually occurs as ammonium salts. The major components of human urine are given in Table 1.

Urine with diverse bacterial composition is dominated by Proteobacteria (37%) followed by Bacteroides (29%), Chloroflexi (15%), Planctomycetes (5%), and other smaller communities forming <14%. This microbial composition of urine is determined by using the 16S rRNA gene sequence approach. Proteobacteria dominate in urine (Williams et al., 2019). Some other bacterial communities are members of *Pseudomonas*, Anaerolinaeae, Methyloversatilis, and *Nitrospira* (Lucker et al., 2010; Daims et al., 2015; Kalyuzhnaya et al., 2019; Smalley et al., 2019).

2.1.2. Characteristics of urine

The volume of urine varies depending on the amount of fluids consumed. An adult human urinates on an average of 1200–1500 mL of urine daily. Normally the color of urine is clear pale yellow to deep amber as a result of urochrome pigment. Unusual color or turbidity of urine indicates serious illness or infection (Bouatra et al., 2013). Specific gravity reflects the ability of the kidney to concentrate urine and aids in the diagnosis of various renal diseases, value varies from 1.010 to 1.030. It can be determined with a urinometer. Osmolarity is the measure of moles dissolved in a kilogram of solvent. It provides an accurate concentration of dissolved substances and is more important than specific gravity determination (Patel et al., 2020). The normal osmolarity of urine of a healthy human should be greater than 800 mOsmol kg^{-1}, and after 24 h of storage may vary from 500 to 800 mOsmol kg^{-1} (Liu et al., 2016). Fresh urine is slightly aromatic. It may have a mild smell sometimes but not any foul odor. Density ranges between 1.003 and 1.035 g cm^{-3}. Fresh urine is slightly neutral with an average of pH 6.2 (Rose et al., 2015), within a range of pH 5.5–7.0. Diet is a major factor in the pH determination of urine.

2.2. Separation and collection of human urine

Source separation of urine not only enhances the efficiency of wastewater management but improves the effluent quality, saves energy utilization and their investment cost (Wilsenach and van Loossdrecht, 2003). The efficient method of separation of urine is in toilets itself as it enables the collection of a large number of nutrients and returning them to the soil, thereby closing the cycle. This is possible with toilets where the bowl is divided into two parts for separate collection of urine and feces as in ecological sanitation (ECOSAN) systems, urine diversion toilets, and no-mix toilets (Larsen et al., 2001, 2009). Volume reduction, stabilization, nutrient extraction, handling of micropollutants, and pharmaceutical sequestration all are a major output of urine source separation and main objectives of urine treatment (Ishii and Boyer, 2015; Lam et al., 2015; Landry and Boyer, 2016; Tarpeh et al., 2018). In urine-diverting dry toilets, separation of urine and feces occurs at the source through the use of a squatting pan (generally referred to as the user-interface) in which feces fall through a large drop hole, whereas urine is drained via a basin having a small hole, thus making possible to collect pure urine without dilution with water. Urinals used by men work as urine diversion devices as urine is easily collected separately from feces (Munch and Winker, 2011).

Table 1
Constituents of human urine and respective composition (Putnam, 1971; Kirchmann and Pettersson, 1995; Oosterhuis and van Loossdrecht, 2009; Karak and Bhattacharyya, 2011; Sarigul et al., 2019).

Constituents	Composition (%)
Water	96
Urea	2
Potassium	0.6
Sulfate	0.18
Phosphate	0.12
Sodium	0.1
Creatinine	0.1
Chloride	0.06
Ammonia	0.05
Uric Acid	0.03
Calcium	0.015
Magnesium	0.01
Others (Oxalate,Amino acids, Phospholipids)	0.635

2.3. Technologies for conversion of human urine into useful products

Various techniques have been explored to maximize nutrient recovery from human urine. The fiscal expenditures, energy consumption, and technicalities of each technique are important considerations. In the treatment process of urine by magnesium dosing, complete recovery of P can be achieved by adding compounds like magnesium chloride, magnesium oxide, magnesium hydroxide to urine (Wilsenach et al., 2007; Barbosa et al., 2016). Magnesium dosing is governed by pH and Mg to P ratio; optimum pH range being 8–10.5 and Mg:P be 2:1 for maximum P-recovery (Liu et al., 2014a; Barbosa et al., 2016). Other ions like sodium, calcium, iron, aluminium can be added to urine for phosphorus precipitation (Chipako and Randall, 2020). Generally, 96% of the phosphorus can be precipitated as amorphous calcium phosphate on calcium dosing by adding calcium oxide, calcium hydroxide, or calcium carbonate for urea stabilization and precipitation (Pradhan et al., 2017). Favorable conditions are a temperature of 25 °C and high pH value ranging from 11 to 13 (Randall et al., 2016). Chemical dosing is not suitable for nitrogen recovery from urine because, after urea hydrolysis, nitrogen is lost due to ammonia volatilization (Randall et al., 2016). So, nitrogen is recovered through ammonia stripping in which ammonia gas produced after ammonia volatilization is recovered, exposed to the acidic solution (sulphuric or acetic acid), and reclaimed in form of products like ammonium sulfate (Başakçilardan-Kabakci et al., 2007). Another effective nitrogen recovery method is adsorption in which ammonium ions are adsorbed to the electronegative surface of adsorbents through cation-exchange processes (Allar and Baykal, 2015; Tarpeh et al., 2017). Activated carbon is a good adsorbent choice (Mazlan et al., 2016). Volume reduction by removing water from urine (by physical removal method, eutectic freeze crystallization, evaporation, or reverse osmosis) is the best technique of recovering the valuable nutrients from it, as the remainder will be the concentrated product rich in nutrients (Sakthivel and Chariar, 2013). Evaporation is followed by distillation to reclaim water vapors (Udert and Wachter, 2012). In reverse osmosis, only water molecules of urine are passed through the membrane and result in the production of brine (which could be used as a liquid fertilizer) consisting of high concentrations of salts and nutrients (Ek et al., 2006). Other membrane processes like membrane distillation, nanofiltration, and forward osmosis can also be used (Maurer et al., 2006; Zhang et al., 2014; Ray et al., 2019). Fig. 1 represents different technologies that can be used for human waste (urine) management.

3. MFC configuration and types

In recent times, MFCs have gained great attention for generating bioelectricity as well as simultaneous recovery of nutrients from ideal waste feedstock i.e., urine. MFC is a type of bioelectrochemical device that involves the utilization of microorganisms, biological processes, and enzymes in the simultaneous production of electricity and other resources like biohydrogen, nutrients (Ivase et al., 2019) from wastes. MFCs convert the locked chemical energy of organic and inorganic components into electric current under influence of a 'live engine' (i.e., bacteria, microalgae, and fungi) which catalyzes the degradation of such

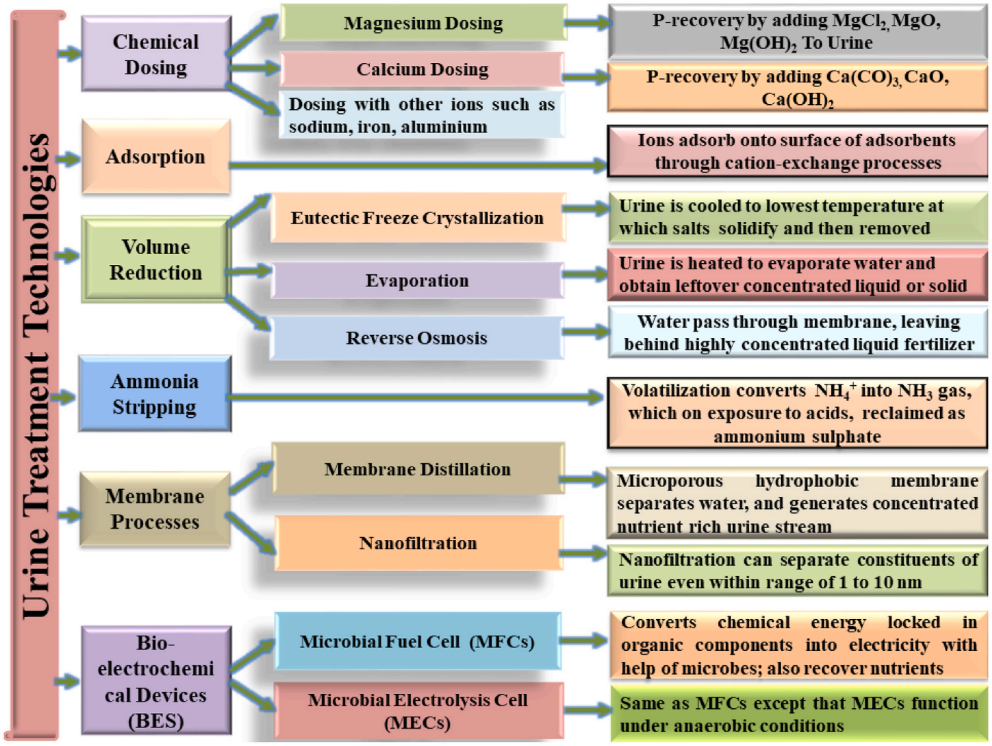
Urine Treatment Technologies
Chemical Dosing
Magnesium Dosing
Calcium Dosing
Dosing with other ions such as sodium, iron, aluminium
P-recovery by adding $MgCl_2$, MgO, $Mg(OH)_2$ To Urine
P-recovery by adding $Ca(CO)_3$, CaO, $Ca(OH)_2$
Adsorption
Ions adsorb onto surface of adsorbents through cation-exchange processes
Volume Reduction
Eutectic Freeze Crystallization
Evaporation
Reverse Osmosis
Urine is cooled to lowest temperature at which salts solidify and then removed
Urine is heated to evaporate water and obtain leftover concentrated liquid or solid
Water pass through membrane, leaving behind highly concentrated liquid fertilizer
Ammonia Stripping
Volatilization converts NH_4^+ into NH_3 gas, which on exposure to acids, reclaimed as ammonium sulphate
Membrane Processes
Membrane Distillation
Nanofiltration
Microporous hydrophobic membrane separates water, and generates concentrated nutrient rich urine stream
Nanofiltration can separate constituents of urine even within range of 1 to 10 nm
Bio-electrochemical Devices (BES)
Microbial Fuel Cell (MFCs)
Microbial Electrolysis Cell (MECs)
Converts chemical energy locked in organic components into electricity with help of microbes; also recover nutrients
Same as MFCs except that MECs function under anaerobic conditions

Fig. 1. Various technologies for the treatment of human urine.

components (Singh et al., 2018; Chipako and Randall, 2020). MFCs extend remarkable benefits like improved sanitation, energy-saving, waste treatment, and energy conversion. A successful pilot-scale MFC fed with urine from public toilets in the Glastonbury Music Festival had been run by Ieropoulos et al. (2016) for 90 d to generate 75 mW of power each day, 98% removal of COD, and 63–79% removal of total nitrogen removal with low operational energy. This worldwide popular technology needs to be exploited at a large scale for power production and nutrient recovery.

3.1. Components of MFC

A typical MFC design consists of one chamber having an anode and the other containing cathode; both connected with wires of titanium or copper to form an electrical circuit. Electrode materials must possess high electron conductivity, a large surface area, less price, high porosity, and good biocompatibility for microbial adherence to the surface for biofilm formation. Surface properties of an electrode such as roughness, porosity, and surface hydrophilicity affect biofilm formation which subsequently affects the production level of electric power in MFCs (Pant et al., 2011; Wang et al., 2016; Zhao et al., 2017). Between two chambers lies a proton exchange membrane (PEM) that is permeable to protons produced at the anode and allows them to move towards the cathode. In the following subheads, these three main components of MFCs are discussed.

Anode: Conductive, chemically inert to the electrolyte (anolyte), and environmentally friendly (non-fouling) material is used to make anode. Ideally, it should have a high specific surface area, conductivity and porosity, and non-corrosive characteristics (Prakash et al., 2010). Carbon electrodes can be widely used in MFCs including carbon paper (Zhang et al., 2012), carbon cloth (Hou et al., 2014); carbon fiber (Xiaojing et al., 2016), carbon felt (Zhang et al., 2016), carbon graphite brush (Yang et al., 2016), graphite plates and granules, stainless steel (Liu et al., 2014b). A brush-like carbon veil structure with large space available for biofilm formation can be used to increase the electrode volume. A bare electrode with a lesser surface area can be used after modification with conductive nanomaterials having a high surface area (such as graphene) to increase the performance of MFC (Jiang et al., 2014; Shen et al., 2014; Tang et al., 2015). Thus, anode material that exhibits both electrochemical performance and biocompatibility is a major concern. Some studies have shown that three-dimensional (3D) structure is very beneficial in improving the anode performance (Hou et al., 2014, 2015).

Cathode: Carbon paper is the most common material used for making cathode. It is encumbered with a catalyst on one side whose function is to increase the oxygen reduction reaction rate (Logan, 2007). Being cheap, abundantly available, and owing to high electrode potential, oxygen is the best alternative for electron acceptors. The value of power density values reduces by 10 times in the case of plain carbon cathodes in comparison to catalyst-coated cathodes (Logan, 2007; Huang et al., 2012). High power density values can be reached by merely increasing the surface area of the cathode (Reimers et al., 2006). Nowadays, cathodes adhered with biocatalysts (microorganisms) instead of chemical catalysts are commonly used. These biocathodes are more beneficial than abiotic cathodes because they utilize alternative possibilities along with wastewater treatment in the anode (Rahimnejad et al., 2015).

Proton Exchange Membrane (PEM): It is a major and crucial component of MFCs and is permeable to cations/protons allowing their passage from anodic to the cathodic chamber (Heilmann and Logan, 2006). Material for PEM must be carefully chosen and it should be permeable. However, extremely porous material through which fluid passes easily must be avoided. The surface area of PEM plays important role in power generation. It is observed that electricity output decreases if the surface area of PEM is lesser than the area of electrodes. It is due to internal resistance (Oh and Logan, 2005). Various materials have been used for the PEM by researchers. Nafion is one of the most commonly used materials for PEM. A mixture of agar, NaCl, and distilled water had been used to form PEM (Bhardwaj and Babu, 2012). Ceramic membranes are also used as separators owing to their lower cost, natural availability, chemical, and thermal stability, durability for long-term uses, ease of adaptation with different-scaled designs, and catholyte production. Low-cost non-woven cloth separators have been used in

long-term operations (Fan et al., 2012; Kim et al., 2016). Many pilot-scale MFCs have been successfully operated even without PEM, attaining COD removal rates ranging from 41 to 80% (Jiang et al., 2011; Narayanan et al., 2012; Hiegemann et al., 2021; Tang et al., 2019; Jadhav et al., 2020). A membraneless MFC reduces its manufacturing cost due to a lack of PEM and an expensive catalyst. The first membraneless SCMFC for urine treatment was made of a glass jar of 125 mL capacity with lateral holes for air cathode, it was observed that the power output decreased over time. The working principle of an MFC is graphically presented in Fig. 2. The figure depicts the function of different components of cell, and mode of electricity generation as well.

3.2. Types of MFCs used for urine treatment

The major types of MFCs used for urine treatment include single-chambered MFCs (SCMFC), double-chambered (DCMFC), tubular stacked MFCs, origami star-inspired, and up-flow mode MFCs (Ou et al., 2016; Wu et al., 2016). In Table 2, different MFC-based studies are mentioned that have been successfully used for electricity production from urine.

Single-chamber MFC: SCMFC consists of an air-anode that is exposed to atmospheric oxygen instead of an aqueous cathode, and connected to an anode chamber via PEM. Larger power output is generated here credited to abundant oxygen availability because oxygen is not limited here unlike dissolved aqueous oxygen (Park and Zeikus, 2003; Liu and Logan, 2004). The internal ohmic resistance in SCMFC can be reduced by reducing the distance between anode and cathode (Flimban et al., 2018). SCMFC provides high power output in addition to being simple and economical as compared to DCMFC (Ringeisen et al., 2006). Santoro et al. (2013) were the first to use membraneless single-chambered urine fuelled MFC made from a glass jar having a hole at the side for accommodating an air cathode. In another study, SCMFC was used for the treatment of raw human urine cost-effectively for power production, recovery of nutrients, and removal of contaminants (Pandey et al., 2016). A single-chamber MFC fuelled with urine and augmented with 0.5% yeast extract and 1% tryptone can generate 14.32 W m^{-3} of power after the first stage and 11.76 W m^{-3} after the third stage with simultaneous recovery of struvite ($NH_4MgPO_4{\cdot}6H_2O$) (You et al., 2016). Recently, the possibility to use a membraneless SCMFC with air-cathode has been checked. Such MFCs have been found with high electricity output, and efficient total nitrogen removal at high TAN (total ammonia nitrogen) concentrations (Wang et al., 2017). A modified membrane-less single-chambered MFC with a carbon-felt air cathode and anode "buried in biologically active soil" has been recently used to treat urine with a peak power output of 124.16 mW m^{-2} only after 24 h. However, 70.75 mW m^{-2} of power was obtained after three weeks of installment (Simeon et al., 2020).

Double-chamber MFC (DCMFC): The simplest and typical MFC is DCMFC which consists of two chambers viz. anodic and cathodic made of either glass or plastic, contains electrodes, and are separated by PEM that is permeable to protons and are connected via wire (Du et al., 2007; Kumar et al., 2017a). Generally, a substrate in the anodic chamber and a catholyte in the cathodic chamber of DCMFC are used to generate electricity. Rather than using heterotrophic bacteria for oxygen supply, photosynthetic microbes (like blue-green algae) and cyanobacteria are in limelight to be used as a biocatalyst in DCMFC (Rosenbaum et al., 2010). Sharma and Mutnuri (2019) used diluted raw urine samples to access the performance of MFC using mixed consortia and pure microbial cultures. It was evaluated that mixed cultures showed better COD removal and higher energy recovery than pure cultures (Jothinathan and Wilson, 2017).

Upflow MFC (UMFC): A membrane-less UMFC working in continuous flow was made by Jang et al. (2004). It is a cylindrical MFC in which the anode chamber is present at the bottom, glass wool or glass bead layers at the center, and cathode at the top. A continuous flow of substrate is provided to the anodic chamber which after passing through the cathodic chamber exits from the top (He et al., 2006; Lay et al., 2015). The formation of gradient between electrodes is favorable for MFC (Cheng et al., 2006a,b). UMFC shows high mass-transfer efficiency and cell density (Jang et al., 2004). There is no hindrance in proton transmission as there is no physical parting (Venkata Mohan et al., 2014). UMFCs can be easily scaled up and hence most preferable for wastewater treatment, but the energy cost to pump substrate is high than power output (Brutinel and Gralnick, 2012; Zhou et al., 2013). Conclusively, the principal purpose of UMFC is wastewater treatment rather than electricity production.

Tubular Packed-Bed MFC: These reactors are tubular, filled with solid catalyst, operate in presence of oxygen or other chemicals (like ferricyanide) as catholyte, and are often used to catalyze gas reactions (Jang et al., 2004; Scott et al., 2007). A tubular reactor consisted of two anodes and two cathodes in the same electrolyte and surrounding single ceramic support, and a 2 mm perforated acrylic sheet separating anode from cathode has shown approximately 500 μW of power generation (Walter et al., 2016b). Fixed-bed MFC has been recently used for

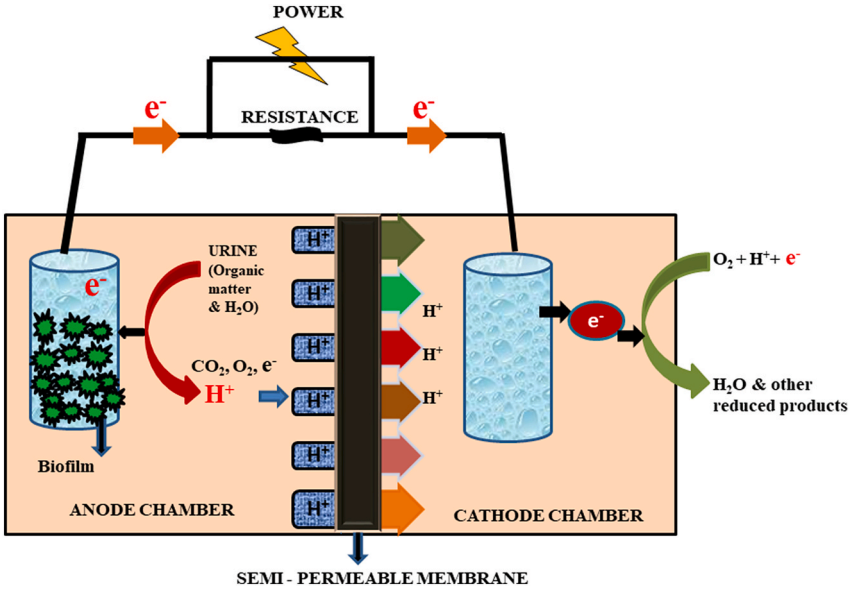

Fig. 2. Illustration of working principle of urine fed Microbial Fuel Cell (MFC).

Table 2
Different studies based on human urine fed MFCs.

S. No.	Type of MFC used	Specific experimental conditions	Anode	Cathode	Inoculum	Power output/ power density/ voltage	Nutrients recovered/Pollutant removal	References
1	Single-chamber MFC	Temp. 25 °C	Carbon felt	Pt-coated Carbon paper	Completely hydrolyzed urine	900 mW m^{-3}	Removal: PO_4^{3-}: 94.6% NH_4^+: 28.6% COD: 64.9%	Zang et al. (2012)
2	Single-chamber air-cathode MFC	Temp. 25 °C	Carbon felt	Pt-coated carbon paper	Five times diluted urine with phosphate dosage of 620 mg L^{-1}	Max: 99 μW	NH_4^+ removal: 40% NH_4^+ recovery: 27.9% PO_4^{3-} recovery: 42.6–62.4%	Zang et al. (2012)
3	Double-chamber air-cathode MFC	Temp. 20 °C Flow rate- 10 mL min^{-1}	Graphite felt	Pt coated Ti felt	Real urine	2500 μW	NA	Kuntke et al. (2012)
4	Stacks of miniature MFCs	Temp. 22 °C pH: 6.4	Carbon fibre veil	Carbon fibre veil	Activated anaerobic sludge	1.5 mW Power density- 4.93 mW m^{-2}	NA	Ieropoulos et al. (2013)
5	Single-chamber MFC	Temp. 30 °C	Carbon brush with titanium wire core	Carbon cloth	Real urine	55 μW	75% COD removal	Santoro et al. (2013)
6	Stacked MFC	pH: 6.4	Carbon fibre veil	AC-carbon fibre veil	Neat human urine	Maximum of 14.32 W m^{-3} Absolute power: 358 μW	82% of PO_4^{3-} and 20% of COD removal	You et al. (2014)
7	Air-cathode MFC (batch-mode)	Temp. 30 °C	Graphite fiber	Carbon cloth	Fresh urine	217.63 μW	TN removal: 84.9% COD removal rate: 1078.0 g/m^3/d NH_3^- recovery: 52.8%	Zhou et al. (2013)
8	Stack of three single-chamber air-cathode miniature MFCs (connected in parallel)	Flow rate-0.36 $mLmin^{-1}$	Carbon cloth (threaded with titanium wire)	Carbon cloth (threaded with titanium wire)	Artificial urine medium	0.4551 μW	NA	Chouler et al. (2016)
9	Tubular Air Cathode		Carbon fiber veil	Activated carbon and PTFE mixture	Fresh urine	NA	COD removal- >90%	Ieropoulos et al. (2016)
10	Membraneless single-chamber air-cathode MFC	Temp. 32 °C	Carbon cloth	Carbon cloth as base material, AC powder as catalyst, carbon black as conductivity enhancer, PTFE as binder	Urine with urea concentration 80–3940 mgL-1	3.2 W m^{-2}	TN removal: 31–84%	Wang et al. (2017)
11	Ceramic MFC	Non-fluorinated binders like silicone, polyvinyl chloride, Ludox and chitosan were used. Feed rate: 216 $mLday^{-1}$	Carbon veil	AC-Carbon veil	Mixture of sludge and neat human urine (1:1 v/v)	510 μW with chitosan binder	Maximum of COD removal reached in chitosan-based MFCs - 26%	Salar-García et al. (2017)
12	Double-chamber MFC	Temp. 20 °C. Flow rate: 1.00 mL min^{-1} and 1.25 mL min^{-1} for Anolyte and catholyte, resp.	Carbon Felt/ Carbon Paper	Carbon Paper	Anaerobic sludge and Real Urine	332 mWm^{-2}	COD removal: 75.5%	Barbosa et al. (2017)
13	Stacked MFC	Addition of sea salts to urine	Carbon veil	AC -Polytetrafluoroethylene (PTFE)	50:50 mixture of activated sewage sludge and fresh urine	50:50 mixture of activated sewage sludge and fresh urine	Struvite recovery- 94%	Merino-Jimenez et al. (2017)
15	Single-chamber MFCs	pH: 8.6–9.4	Carbon fibre veil	Activated carbon	Mixture of sludge and sodium acetate	1.516 mW	Catholyte generation and precipitation of iron, copper, zinc	Gajda et al. (2017)

(*continued on next page*)

Table 2 (*continued*)

S. No.	Type of MFC used	Specific experimental conditions	Anode	Cathode	Inoculum	Power output/ power density/ voltage	Nutrients recovered/Pollutant removal	References
16	Two ceramic stacks- (t-stack and m-stack)	Temp. 22 °C	Carbon fibre veil	Carbon cloth	50% Activated sewage and 50% urine	m-stack: 0.8 mW t-stack: 0.52 mW	NA	Tremouli et al. (2018)
17	Two stacks of 32 individual cells (connected in series)	A gravity-driven crossflow through each stack was made	Carbon veil	Carbon veil with micro pores	1:1 solution of human urine and activated sludge	Power density: 23 mW m^{-2} Current density: 65 mA m^{-2}	COD removal- 80% when stacks were independent, 70% when connected in parallel, and <50% when in series.	Cid et al. (2018)
18	Small scale ceramic MFC	Metal-carbon-derived electrocatalyst containing iron and nicarbazin	Carbon veil	Carbon veil	Activated sludge and urine (1:1)	1.82 mW	NA	Gajda et al. (2018)
19	Stacked MFC	pH: 8.3–8.9 Solution conductivity: 24–28 mS cm^{-1}	Carbon fiber veil	AC-SSM -PTFE	Real Urine	11 W m^{-3}	NA	Walter et al. (2018)
20	Two-chamber MFC (batch mode)	Temp. 25 °C Flow rate- 10 mL min^{-1}	Stainless steel mesh	Stainless steel mesh	Raw urine	Voltage: 0.645 V	NH_4^+ removal: 49.96% NO_3^- removal: 54.28% Ortho-P removal: 94.2% COD: 69.97%	Sharma and Mutnuri (2019)
21	Single-chamber air-cathode MFCs (batch mode)	Temp. 32 °C	Carbon clothes	Carbon cloth [with platinum pasted on one side using Nafion, and PTFE on other side]	Synthetic urine (COOH-THC concentration: 50 $mgm^{-1}L$)	102–155 mW m^{-2}	94% COD removal	Ozdemir et al. (2019)
22	Ceramic MFC	Flow rate- 0.06 mL min^{-1} Iron-based catalyst	Carbon veil	Active part of the cathode faced terracotta whereas stainless steel exposed to air	Sludge and human urine (1:1 v/v)	104.5 μW cm^{-2}	NA	Salar Garcia et al. (2019)
23	Single-chamber MFCs	pH: 6.4–7.4 Temp. 22 °C	Carbon fiber veil	Activated carbon(AC)-PTFE-stainless steel mesh (SSM)	Real Urine	3–5 mW	NA	Walter et al. (2019a)
24	Supercapacitive MFC	Flow rate: 0.041 mL min^{-1}	Carbon veil	Activated carbon (AC)	Fresh urine	1.20 mW at 0.01s and 0.65 mW at 5s time pulses	NA	Santoro et al. (2019)
25	Three-chamber MFC with air-cathode (batch)	Temp. 30 °C	Graphite fibre brush	Activated carbon air-cathode	Synthetic Urine (ten-times diluted urine)	Power density: 1300 mW m^{-2} Voltage: 0.72 V	Removal: Urea - 99% COD- 97% Histidine- 99% Creatinine- 91% Sodium acetate- 99%, SO_4^{2-}-98% PO_4^{3-} −99% TN- 42%. Recovery of 33% of total salts	Lu et al. (2019)
26	Denitrifying fuel cell system	pH: 7	WO_3 nanoanode	Produced with bimetallic plating method	Artificial urine	2.24 mW/ cm^2	Removal: Total nitrogen (TN)- 99.02% Total organic carbon (TOC)- 50.76%	Shen et al. (2019)
27	Single-chamber air-cathode MFCs	Platinum catalyst	Carbon cloth.	Carbon/ polytetrafluoroethylene	Both Synthetic and Real human urine	Voltage: 0.2–0.26 V	Benzoylecgonine levels decrease by 14%	Catal et al. (2019)
28	Air-breathing single-chamber MFC	Initially batch-fed followed by continuous feed flow rate 0.06 mL min^{-1}	Carbon veil	AC-PTFE-SSM	Mixture of sludge and neat human urine (1:1 v/v)	1.16 mW	NA	Salar-García and Ieropoulos (2020)
29	Ceramic-based MFCs (nine units in one cascade)	pH: 6.5–7.1, Flow rate- 20 mLh^{-1}	Carbon veil	Activated carbon	Neat human urine	1.05–1.28 mW	NA	Obata et al. (2020)
30				Carbon-felt air cathode	Real urine		NA	

(*continued on next page*)

Table 2 (*continued*)

S. No.	Type of MFC used	Specific experimental conditions	Anode	Cathode	Inoculum	Power output/ power density/ voltage	Nutrients recovered/Pollutant removal	References
	Single-chamber membrane-less MFC	Anode was fully buried in biologically active soil	Carbon-felt anode			Average power: 70.75 mW m^{-2}		Simeon et al. (2020)
31	Air-exposed biocathode MFC	20–25 °C.	Carbon-felt anode	Carbon-felt air cathode	The electrochemical active nitrogen-removing consortium	Maximum power densities of 65 mW m^{-3}	Removal: NH_4^+- 86.8% TN- 62.7% COD- 52.7%	Yang et al. (2020)
32	Stacked MFC	Flow rate- 104 mL min^{-1}	Stainless-Steel mesh	Stainless-Steel mesh	Mixture of anaerobic digestate and mineral salt media	Power density: 14.5 mW/m	Removal: COD- 75.55%, Ortho-phosphates- 90% Ammoniacal nitrogen- 46%.	Sharma et al. (2021)
33	Air-breathing MFC	pH: 8.8–9.2, Solution conductivity: 27–30 mS cm^{-1}). Flow rate- 3.5 mLh^{-1}	Carbon veil	AC-PTFE mixture	50% partially hydrolyzed urine	1045.3, 655.8 and 286.6 μW at 1100, 1200 and 1300 °C, resp.	NA	Salar-Garcia et al. (2021)
34	Ceramic MFC (6 MFCs assembled with fine fire clay ceramic cylinders)	Flow rate- 9 mLh^{-1}	Carbon veil	Activated carbon powder- 20% PTFE solution	Anaerobic activated sludge	3 mW.	NA	Merino-jimenez et al. (2021)
35	12 MFCs (assembled using fine fire clay cylinders)	Temp. 22 °C. Flow rate- 9 mLh^{-1} Initial COD- 8.1 ± 0.4 g L^{-1}.	Carbon veil	AC-PTFE	50% activated sewage sludge and 50% fresh urine After inoculation phase, feedstock was 100% fresh urine	2.1 mW	COD reduction of 15.5, 14.5, 13%, respectively for thin, medium, thick ceramic MFCs	Merino-jimenez et al. (2021)

NA: Not Available.

electricity generation from urine. It was observed that by increasing bed thickness from 5 to 10 mm, 1.6 times higher current density was generated. Also, moving bed produced twice the power output as that of fixed bed current over full charging and discharging cycles (Borse et al., 2021).

Origami Star-Inspired Fuel Cell: Origami tetrahedron MFCs with urine as substrate had been first used by Winfield et al.(2015) to provide power to portable emergency locator transmitters. Origami, the Japanese art of paper folding which is star-shaped and opens into a Frisbee-like ring has inspired an MFC design. The ring contains both electrodes and a PEM. There is an inlet at the center for the addition of substrate and inoculum of microbial culture. When the cathode is exposed to air, it reacts with oxygen-producing energy for biosensors and other portable devices (Fraiwan and Choi, 2016). In a recent study, stacked origami MFCs are used as a substitute for the conventional power source for a smartphone (Nath et al., 2020).

4. Mechanism of electricity production from human urine in MFCs and their performance

In an MFC, electricity is generated through urine oxidation in an anode chamber by catalytic activities of microorganisms, which gives rise to the generation of electrons and protons (He et al., 2005). The electrons flow to the cathode from the anode through an external circuit, while the protons diffuse through PEM to a cathodic chamber (Rabaey and Verstraete, 2005). Protons and electrons merge with oxygen at cathode to complete the redox reaction cycle and produce water molecule, and chemical energy of the biomass is converted into electrical energy (Rahimnejad et al., 2011; Pandit et al., 2017; Palanisamy et al., 2019; Sarma et al., 2021). There are three mechanisms of electron transfer from bacteria to the electrode that are described below as well as shown in Fig. 3 for easy understanding.

a) Direct Electron transfer (DET): The mechanism is based on the direct transport of electrons produced in the anodic chamber after oxidation of organic matter by exoelectrogens microbes. It can be achieved with help of redox-active proteins present on the bacterial membrane (for instance, c-type cytochromes, multi-heme proteins) and pili (Pandit et al., 2014). In electrochemically treated graphite felt electrodes that are inoculated with *Desulfovibrio desulfuricans*, and where cytochrome-c is involved in electron transfer, a maximum current density of 233 mA m^{-2} can be generated (Kang et al., 2014). Bacterial cells are usually present near electrodes in the case of monolayer biofilms and produce current.
b) Electron transfer via conductive appendages (termed 'nanowires') developed by bacteria on their surface: *Geobacter sulfurreducens* is an exemplary microbe for elucidating the mechanisms of electron transfer via conductive appendages in several biogeochemical cycles, bioelectrochemical applications, and metal corrosion. Many pieces of evidence suggested that electrically conductive pili are important channels for long-range extracellular electron transport in *G. sulfurreducens* (Malvankar et al., 2014). The bacteria produce type-IV conductive pili composed of PilA protein (i.e., the nanowires) which are capable of transporting electrons between biofilm and electrode surface. By using electrostatic force microscopy, it is confirmed that charge propagation takes place from cell to cell through pili. In multilayer biofilms, nanowires (pili) helps in long-range electron transport as only a few cells have direct access to electrodes, the conductive biofilms possess a dense pili network which shows metal-like conductivity and enables the generation of

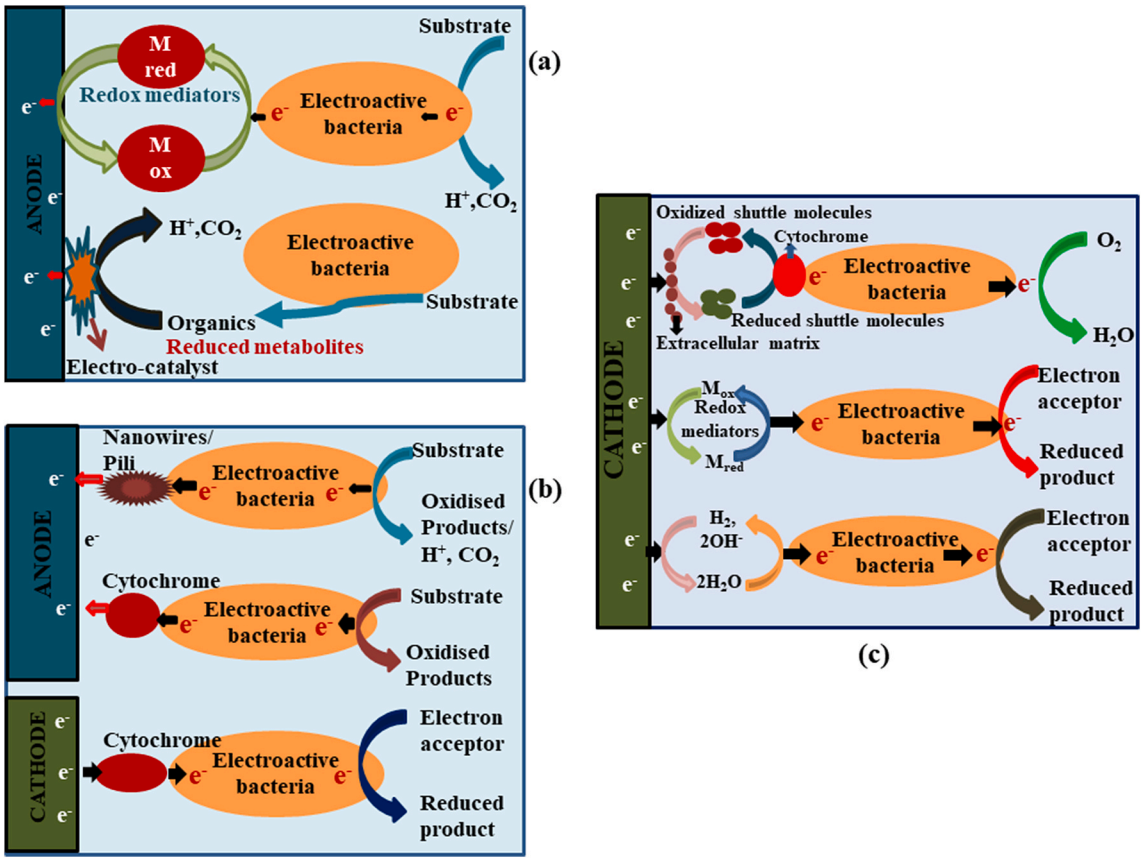

Fig. 3. Electron transfer mechanisms (a) mediated electron transfer from bacteria to the anode through redox mediators and via reduced metabolites (b) direct electron transfer from microbes to the anode through appendages and cytochrome, and from cathode to anode through cytochrome (c) indirect electron transfer from cathode to the anode through redox mediators, oxidation of hydrogen and shuttle molecules.

current (Lovley and Walker, 2019; Lovley and Holmes, 2020). Liu et al. (2021) reported that about 90% of filaments emanating from microbial cells are e-pili whereas 10% filaments possess c-type cytochrome (OmcS) demonstrating that e-pili are 10 times more abundant and very important conductive filaments than OmcS for long-range extracellular electron transfer.

However, it was contradicted after cryo-electron microscopy of cell structure that instead of PilA, *G. sulfurreducens* nanowires are assembled by polymerization of hexaheme cytochrome [OmcS], with hemes packed within ~3.5–6 Å of each other. This structure explains the remarkable capacity of bacteria to transport electrons to electron acceptors for energy production (Wang et al., 2019). Yalcin et al. (2020) also supported that multiheme c-type cytochromes (OmcS and OmcZ) are the important functional conduits responsible for long-range extracellular electron transfer. Moreover, a recent study showed that the two genes (PilA-N and PilA-C) of the bacteria bind with each other to assemble heterodimeric pili (PilA-N–C) through electrostatic and hydrophobic interactions positioning PilA-C towards the outer surface of PilA-N–C filament. This heterodimeric pili remains in periplasm under nanowire-producing conditions, and it is 20,000-fold less conductive than OmcZ nanowires. OmcS and OmcZ nanowires cannot be secreted when pilA-N is deleted but restored when PilA-N–C filaments are formed. This concludes that though PilA-N–C filaments do not show high conductance, but they are crucially needed for secretion and translocation of OmcZ and OmcS nanowires for long-range extracellular electron transfer (Gu et al., 2020).

c) Transfer through secondary mediator biomolecule: The redox-active entities known as 'mediator' establish electric linkage between bacterial cell and electrode, which make electron transfer possible. Mediators are usually an outer membrane redox protein, soluble redox-shuttle, or reduced metabolites (Logan et al., 2006). Mediators generally include two categories (1) exogenous or artificial redox mediators, and (2) soluble electron shuttles secreted by microorganisms (Barton et al., 2004). Compounds of quinones, phenazines, phenoxazines, and phenothiazine are used as exogenous or artificial redox mediators (Rabaey et al., 2007; Mohan et al., 2008), but due to a few disadvantages such as low current density and regular addition of mediator, this approach is least used.

Though urine-fed MFCs are an effective tool for bioelectricity production, there are some challenges of using urine in MFCs, especially for power production. A high concentration of ammonia in urine creates a hindrance when operating MFC at a higher organic loading rate. Moreover, a high organic loading rate imbalances the pH which further challenges the functioning of MFCs. Urine can be used in MFCs only if it contains a certain concentration of urea. Urine released in houses is diluted and can be used easily but when it reaches the treatment plant, it gets contaminated with many chemicals, and a major concentration of urea gets decomposed into ammonia which makes the operation of MFCs problematic. Also, urine cannot be used on a broader scale due to extortionate transport costs. The spread of pathogens and organic micropollutants and odor generation hampers the utilization of urine in MFCs. Urine needs to be hydrolyzed before their use in MFCs to lower down the phosphorous content because phosphorous precipitates on the anode and affect the electrode performance by decreasing the biotic/abiotic interface. Phosphorous precipitation is unfavorable for cathode because it increases mass transfer resistance by inorganic fouling and deactivation of cathode catalyst.

5. MFC modifications for enhanced electricity production

There are numerous challenges associated with MFC technology; high capital and operating costs (expensive electrode and membrane materials, catalysts) and low power output are the most important shortcomings. Other challenges include high potential loss at the surface of electrodes leading to a reduction in current density, inability to recover heavy metal ions, selection of suitable substrate and high-performance electrode, appropriate as well as safe scaling-up of MFC units for economic evaluation and performance enhancement (Pandit et al., 2021; Wu et al., 2021). Despite these obvious and well-known challenges, recent years have seen progress towards upscaling and practical application of the MFC technology. Using large air cathodes, 85 L (Rossi et al., 2019) and 255 L (Hiegemann et al., 2021). MFCs were reported treating domestic and municipal wastewater respectively. Similar efforts for MFCs treating urine are expected in the coming years. Much advancement has been made to overcome many of these challenges and drawbacks that hinder the commercialization of MFCs. For instance, modified electrodes are used, stacking of individual units is promoted, modified catalysts are incorporated, and improved processes are involved in the MFCs for enhanced electron transfer (Tiquia-Arashiro and Pant, 2020)). Electrodes have been improved through different strategies, for example, candle-soot modified electrodes, anode prepared with a mixture of porous tetrahedral-zeolite clay and graphene oxide, carbonaceous anode modified with graphene oxide/graphene oxide-zeolite, anodes modified with micro and nano-scale carbon particles are popular nowadays (Singh et al., 2020). Anodes possessing excellent biocompatibility and electrochemical performance are preferable. Cathodes are modified concerning catalyst selection and cathode height. Another strategy adopted is connecting external supercapacitors to MFCs to boost the current output, and scaling-up membrane-less MFCs to minimize power density losses. In the following subheads, a few modifications of urine-fed MFCs are discussed.

5.1. Use of carbon-based and carbon-composite nanostructured electrodes

Electrodes made from carbonaceous substances such as carbon nanotubes, carbon black, nanofibers, graphene are widely used for electrode making. Owing to their high surface area, good electrical conductivity, excellent mechanical properties, and better stability; nanostructured materials possess high potential to improve the efficiency of MFCs (Kumar et al., 2013; Li et al., 2017). Three-dimensional (3D) structures add more to electrode performance (Hou et al., 2014). 3D anode fabricated from spongy nanotube structure possesses a hydrophilic surface and good biocompatibility and hence provides many advantages like high voltage output (up to 231.89 mV), and high power density (1.24 W m^{-3}) (Zhao et al., 2017). Chitosan helps in improved microbial adhesion on the electrode surface; so, carbon nanotube-chitosan composites can be used to modify electrodes. MFCs with carbon-nanotube-chitosan anode show current and power density increased by 23% and 65%, respectively when compared to a carbon-paper-based pure anode (Liu et al., 2014b). Metal oxide nanoparticles have been used to modify the surface properties of carbon-based materials (Mehdinia et al., 2014).

Activated carbon (AC) is cost-effective, easily available, durable over a long period, and has a high specific area. Due to these properties, AC is found useful to be used as a capacitive electrode (Zhang et al., 2014; Deeke et al., 2015). It can be used in granular form, enables separation of charging and discharging process, and helps in achieving useful rates of oxygen reduction rates in MFCs. AC has been used in combination with other substances also. For instance, Zhang et al. (2014) produced a power density of 1220 mW m^{-2} with AC- polytetrafluoroethylene cathodes, 1626 mW m^{-2} of power output was obtained by using anodes made from AC-micronanostructure on carbon fibers (Gajda et al., 2020). Besides, AC can be used in a mixture with ethylenediaminetetraacetic acid, carbon black (Zhang et al., 2014). It is concluded that up to 10 times increase in current can be achieved with electrodes modified with AC or AC-combinations.

5.2. Integration of self-stratified and self-powered individual MFCs

Modification by stacking a multitude of MFCs and exploiting the system to maximum power output is a promising approach. By combining individual units in series and parallel combinations, horizontally or vertically, enhanced performance of the system can be achieved in terms of voltage as well as current (Ledezma et al., 2013). Assembling plurality of self-stratifying membraneless MFCs is a popular modification concept, nowadays (Walter et al., 2016b). The source of power in self-powered MFCs is redox reactions that occur at two electrodes. When stored electrostatic charges are discharged in the MFC, counter-ions are released into the electrolyte which makes the electrodes self-polarised due to redox reactions occurring on them, and then they attract counter-ions from the electrolyte back to them (Santoro et al., 2019). Modified stacked designs have been used by a few researchers, for instance, a membraneless stacked design with wholly submerged anodes and partly submerged cathodes in urine was applied by Walter et al. (2016b). The cathodes at the top and anodes on the lower half (connected in parallel) constituted a module. Different modules were connected in series. This scaling-up increased power output without any significant ohmic losses (≈12 W m^{-3}). Supercapacitive membraneless MFCs stacked together in series as well as parallel could achieve a power output of about 1.59 mW and 0.57 mW at pulse times of 0.01 s and 2 s, respectively. Connections in parallel were found to produce double the current (Santoro et al., 2020). Sharma et al. (2021) used stacked MFC with 10 L capacity over a period of three months and obtained a voltage of 3.29 V, a power density of 14.5 mW m^{-2}, and 90% and 46% of ortho-phosphates and ammoniacal nitrogen as struvite, respectively.

5.3. Using iron-based catalyst in MFCs for efficient oxygen reduction

To overcome the cost restraint of catalysts that are used in MFCs for oxygen reduction reactions, cheaper catalysts are brought to MFC application, nowadays. Various iron (Fe)-based catalysts have been synthesized using different organic precursors like guanosine, niclosamide, pyrazinamide, quinine, ricobendazole, succinylsulfathiazole, sulfacetamide, sulfadiazine, nicarbazin. iron-ricobendazole, iron-niclosamide, and iron-pyrazinamide have been reported with the highest power densities (about 200 μWcm^{-2}) (Santoro et al., 2017). Performance of cathodes made up of Fe-Streptomycin doped with carbon nanotubes and without doping had been studied (Salar Garcia et al., 2019). Results have indicated that Fe-Streptomycin is a better choice than that doped with carbon nanotubes. Fe-based catalysts are much better than AC and Pt-based (25–44% and 74–100%, respectively) cathodes. These catalysts are up to 55-times more cost-effective than other metal (like Pt)-based catalysts (Santoro et al., 2016; Gajda et al., 2018b; Salar Garcia et al., 2019). Ni-based catalysts have been also used by a few researchers like Xu et al. (2016).

5.4. Modification of MFCs using binders with the cathode (prepared with fluorinated and non-fluorinated polymers)

Binders are the substances used to fix cathode catalysts onto an electrode support material. Presently, many cathodes made with different fluorinated and non-fluorinated polymers are in use. PTFE is one of the most commonly fluorinated binders, however, this is not sustainable and environmentally friendly. Consequently, non-fluorinated polymers like silicone, ludox, chitosan, and polyvinyl chloride are preferred to be used as binders for the cathode. Cathodes prepared with even a small amount of chitosan produce a comparatively higher current, remove more COD, and are 8 times cost-effective than PTFE-based MFCs (Salar-García et al., 2017).

5.5. Promoting halophytic nitrification coupled with aerobic denitrification by inoculating additional active microorganisms in the MFCs

The role of microorganisms in current production is well understood. So, by adding enough nitrogen-removing-consortium in the electrolyte of MFCs, urine degradation can be significantly enhanced even without providing artificial aeration. For instance, removal efficiencies of NH_4^+, TN, and COD can be increased up to 86.8%, 62.7%, and 52.7%, respectively by adding electrochemically active microorganisms like nitrogen-removing bacteria, heterotrophs, halophilic nitrifiers, or nitrifiers in both electrodes (Cui et al., 2016; Barbosa et al., 2017; Yang et al., 2018, 2020; Jin et al., 2019). This modification presents a novel and promising technique for enhanced energy conversion, power generation, and effective degradation of urine in MFCs.

6. Factors affecting the performance of urine-based MFCs

Several factors affect the performance of MFCs in terms of power generation and nutrient recovery. pH, temperature, the height of electrodes, size of the cell, stacking and scalability, flow rate, electrodes, and membrane-type are important among others for maximum output. In addition to these, some other techniques also help to enhance the performance of MFCs like the addition of sea salts in urine before feeding it in MFC which increases electricity production and resource extraction. The idea of adding sea salts to urine was first performed and reported by You et al. (2016). Up to 10% increase in power output, 21–94% rise in struvite recovery, and 16–18% increase in COD removal can be observed (Merino-Jimenez et al., 2017). Pre-fermentation of urine by anaerobic digestion affects the performance of the anode. The employment of this step has been found to increase the COD removal rate as well as average current density. Fermentation converts the complex compounds present in urine like urea, creatinine, and sugars into methylamine, acetate, and propionic acid. Barbosa et al. (2019) used fermented urine and reported that COD concentration stabilizes after 15 d and power of 218 mA m^{-2} was reported. To determine the performance of MFCs, polarization curves and power curves are often used. The polarization curve determines the working voltage of MFC as a function of the current/current density. The power curve determines the point of maximum power transfer in MFCs. In the following subsections, factors that are important in deciding the performance of MFCs are discussed.

6.1. Electrode immersion height

The height of the electrode immersion height affects the performance of MFCs containing urine as electrolytes. Usually, the more the height of the cathode is immersed in urine, the more is the power output. However, it is found that performance lowers drastically when the cathode is submerged fully. The fact is supported by the study of Walter et al. (2019a) who reported that power output of self-stratifying membraneless MFCs increased with cathode immersion height up to three-fourth but performance declined when the height reached complete immersion. This is attributed to the anoxic conditions that establish in the cell when the cathode gets submerged in urine. Complete immersion of the cathode hinders the diffusion of oxygen from the water column surface to the bottom of the cathode. Another report in support of the fact is given by Walter et al. (2019b) who found that minimum power was obtained at 1 cm height of electrodes and minimum height threshold for electrode was between 1 cm and 2 cm. Therefore, it is concluded that maximum power density losses occur at minimum immersion height, and optimum immersion height is more than 50% the height of the electrode in self-stratifying membraneless MFCs.

6.2. Scaling and stacking of MFCs

The scalability of MFCs is optimizing the number of units, electrodes, and cell size for achieving high power output. The most practical approach is stacking several MFC units in series or parallel (Ieropoulos et al., 2016) in which the output of one unit is the input of the next one (Walter et al., 2019b). Increasing the size decreases the power density (Ieropoulos et al., 2008; Walter et al., 2016a; Ghadge et al., 2016). Power output might decline with a rise in the size of the anodic chamber (Penteado et al., 2018; Walter et al., 2020). Moreover, field-level application of bigger-sized MFCs is a bit challenging due to complications in installation and operating procedures, and other engineering and environmental factors (Grattieri and Minteer, 2018). However, by assembling many MFC units in a stacked arrangement, power generation can be effectively increased and ohmic losses can be minimized (Logan, 2010; Walter et al., 2019b; Salar Garcia et al., 2019). Smaller the size of MFC, the greater is the power density. Stacking numerous small-sized MFCs is always more powerful than a single large-sized MFC. The key is in the measurement and maximization of surface area (SA) to volume (V) ratios. More the units in a stack, the more will be the surface area and hence more efficient will be the treatment system and power production (Ieropoulos et al., 2008; Ledezma et al., 2015; Walter et al., 2019b). An MFC stack of capacity 10 L can remove an average of 75.5% COD, recover 90% of ortho-phosphate, 46% of ammoniacal nitrogen, and generate a voltage of 3.29 V from urine over a period of 90 d (Sharma et al., 2021).

6.3. Binder materials of the cathodes

The addition of appropriate binder materials (like polyvinyl-alcohol, PlastiDip, fluorinated and non-fluorinated, carbon nanotube colloidal-silica- based) on cathode affects the performance of MFCs. Polytetrafluoroethylene cathodes can generate 1617 μW of power, polyvinyl-alcohol and PlastiDip can produce on average 1226 μW of power in urine fed MFC. Polytetrafluoroethylene was found as best of the three (Walter et al., 2018). Colloidal silica-based binders are found effective in terms of enhanced electricity generation and COD removal in MFCs (Salar-García et al., 2017) like Ludox aS-40 (Peters et al., 2005). Some other binders had been tried by different researchers like carbon nanotube/chitosan-based cathodes by Liu et al. (2011), chitosan modified with alginate by Krishanaraj et al. (2013). The use of chitosan as binders increases the coulombic efficiency of MFCs. Also, amongst the different binders tested so far, chitosan seems to be the most favorable option because only a small amount of this binder allows MFCs to reach high values of power generation from urine.

6.4. Urine dilution

Dilution and reconcentration of source-separated urine below the solubility limit of struvite are necessary to elude clogging issues in the urine collection system to a centralized treatment facility. The acclimation of electroactive bacteria with increasing urine concentrations leads to rising current densities that do not reach a saturation-like phase which follows a Monod-like evolution profile or Han/Levenspiel-type trend as a function of urine concentration. By diluting un-pretreated urine, current density output values can be increased as high as 3.6 ± 0.2 A.m^{-2} which represents a 35-fold increase compared to power output obtained through undiluted un-pretreated urine (Prudente et al., 2021). It is concluded that microbial acclimation is feasible only within a restricted concentration window. Beyond a certain concentration limit, toxicity effects and precipitation events control the microbial viability and result in low levels of electrical current.

6.5. Effect of pH

pH is an important factor that affects microbial activity in the anodic chamber, proton accumulation, anolyte acidification, redox reactions, and alkalization of electrolytes in the cathodic chamber. Usually, a decrease in pH of the anodic chamber due to proton accumulation is

unfavorable for bacterial growth which ultimately lowers the power production, neutral pH favors the activity of bacteria and is beneficial for oxygen reduction, whereas an increase in pH inhibits the oxygen reduction reaction in the cathode chamber (Ivars et al., 2018). However, in acidic conditions, acidophilic microorganisms proliferate and contribute to power output. Acidophiles are microbes growing at pH < 5 and include archaea, bacteria, and Eukaryota. These microbes utilize several mechanisms to cope with low pH including membranes that are resilient to protons influx, and an internal negative membrane potential that inhibits the influx of protons. Also, the alkaliphiles growing in a pH range of 8.5–11 improve the power generation by adding redox mediators that cause reduction of charge transfer and diffusion resistance. Nevertheless, it is observed that change in the pH towards any extreme side (high or low) produces deleterious effects (Dopson et al., 2016). It is concluded that both the extreme alkaline and alkali conditions do not provide significant power output (Jadhav and Ghangrekar, 2009), a nearly neutral pH value is the most advantageous for higher electric current generation from MFCs (Kumar et al., 2017a), and bacteria accountable for electricity generation in an MFC are generally more active in the pH range of 6 and 8 (known as neutrophiles) in the anodic chamber, and neutral or little higher pH in the cathodic chamber (Obileke et al., 2021). Phosphorous recovery is highly dependent on the pH of the solution. Also, the enzymatic urea hydrolysis in fresh urine occurs in the range of 6.5–11, which results in loss of nitrogen in form of ammonia gas (Randall et al., 2016). The effect of pH on power output is not studied properly yet, and hence the outcome is very complex and requires further research.

6.6. Temperature

Temperature is another significant factor among others that affect the kinetics of the whole MFC system (Amend and Shock, 2001). Temperature affects the MFC operation and power generation by directly affecting electrochemical processes, reactor efficiency, and conversion of electrons in biomass to electricity. MFCs can operate over a wide range of temperature conditions i.e., from psychrophilic to mesophilic to thermophilic conditions. Thermophiles predominantly grow at temperatures above 45 °C and up to a maximum of 122 °C. Mesophilic bacteria grow in a moderate temperature range (20 °C–45 °C). Psychrophiles grow predominantly at a temperature below 20 °C, cellular activity can occur at temperatures as low as −20 °C, and they can reproduce at −12 °C (Dopson et al., 2016). When MFCs operate under thermophilic conditions (>55 °C), bacteria adapt to the high-temperature environment that causes a decrease in diversity but supports only those fewer species that are capable of thermophilic electrochemical activity. The benefit of operating MFCs at thermophilic conditions include higher microbial activity, better substrate solubility, a high mass transfer rate, and a lower risk of contamination. This implies that MFCs might well be capable of operation over an even wider range of temperatures, though the mesophilically adapted communities have the potential for even greater operational flexibility (Michie et al., 2011). An MFC operates best in the temperature range of 25 °C–45 °C as it affects the formation of electrically active stable biofilm, catalytic activity, microbial metabolism, mass transfer, and thermodynamics which ultimately influences the overall performance of the system especially towards electricity generation (Ahn and Logan, 2010; Oh et al., 2010; Patil et al., 2011; Yong et al., 2014; Tang et al., 2015). Moreover, it is necessary to adjust the temperature range for bacterial species as they are stenothermal (Kumar et al., 2015). Increased power density and decreased ohmic resistance is the outcome of rising conductivity due to high temperature (Phung et al., 2004). The enhanced power output as a result of increased temperature exponentially increases the bacterial activity. Temperature above 50 °C can cause chemical hydrolysis of fresh urine resulting in increased ammonia removal during ammonia stripping of hydrolyzed urine (Randall et al., 2016), and found useful for nitrogen recovery (Liu et al., 2014a).

6.7. Flow rate

There are two modes of operation for MFCs, batch mode and continuous mode. In batch mode, urine is provided at the beginning of the cycle. While in the continuous mode, urine is provided after short interims. Shear stress, the flow rate of urine, and hydraulic retention time (HRT) of urine are important factors that decide the performance of MFC and should be optimized to get maximum power output (Zhou et al., 2013; Venkata Mohan et al., 2014). Usually with increasing flow rate; power output, coulombic efficacy, and COD removal efficiency decreases (Sun et al., 2012). High electricity can be generated from a higher organic loading rate (OLR) which in turn depends on the flow rate (Gude, 2016). An increase in the flow rate of urine generates turbulence. Higher OLR values and higher turbulence results in efficient mass transfer to the biofilm and expedite the diffusion and proton-motive potentials, thus improving the electrochemical performance of the MFC (Vigolo et al., 2014). Higher the flow rates, lesser is the HRT i.e., the bacteria get less time for oxidation, therefore, lowering the COD reduction efficiency of MFC. Thicker biofilms are formed due to low shear rates (Logan et al., 2005), whereas higher shear stress declines the microbial diversity resulting in the formation of homogeneous biofilm (Raghavulu et al., 2013). An increase in flow rate increases the power output up to a limit that coincides with critical flow rate (CFR) for maximum specific growth rate (Venkata Mohan et al., 2007; Behera and Ghangrekar, 2009). Flow rates higher than CFR achieve neither higher power nor growth because more nutrients pass through the anodic chamber without reaction, and produced H^+ flows out and removed quickly. If the thick biofilm is present on an impermeable anode, then the rate-limiting factor is the diffusion of the growth-limiting substrate to the bacteria. A faster flow rate will have little effect. If thin biofilm grows on a highly permeable electrode, then the biofilm growth rate depends on the flow rate of rate-limiting nutrients. For a thin biofilm, the power output increases with flow rate (Ledezma et al., 2012).

6.8. Electrode and membrane types

Electrodes are the major constituent of MFC and one of the factors that determine their efficiency. Every electrode has a certain resistance, but the one with the highest efficiency is the least resistive (Juan, 2014). Bio-electrodes are capable of exchanging electrons with electroactive biofilms. To maximize power generation and microbial adhesion, the anode must be porous (Paul et al., 2018). 3D electrodes are highly efficient than 2D electrodes as they exhibit biocompatibility, large bacterial adhesion, and large surface area (Bian et al., 2018). Graphene oxide (GO) owing to rich hydrophilic functional groups, good biocompatibility, and superior electrical, mechanical and optical properties can increase the performance of MFCs (Yong et al., 2014). Conductive polymers like polypyrrole and polyaniline can upturn electrode surface roughness, and cationic nitrogenous groups present in their composite structure can augment cellular adhesion which ultimately increases the efficiency of MFC (Fogel and Limson, 2016).

Membrane plays a key role in determining power output but many more efficient modifications are vital to assess the effect of the PEM on the performance of the MFCs (Min and Logan, 2004; Jafary et al., 2013). The PEM surface area to volume ratio of MFCs determines the power output. Moreover, the membrane determines diffusion of ions or electrolytes resulting in concentration polarization loss which affects the power output and surges the internal resistance of MFC. It is observed that PEM with a larger surface area produces less internal resistance and high current density. In some cases, it was found that MFCs without PEM produce a high power output up to a specific period (Gil et al., 2003). Since these PEMs are costly, the use of membraneless MFCs can be encouraged for large-scale applications in the future.

7. Recovery of nutrients from human urine and their applications

The N, P and K are the vital elements required for high agricultural yields, but the natural supply of these essential elements is limited (Mehta et al., 2015). Though the requirement is met by chemical fertilizers, their high cost and long-term side-effects on soil fertility have driven the search for organic fertilizers. Therefore, the recovery of these critical nutrients from waste streams has gained the attention of scientists worldwide. Researchers have spotlighted the use of urine as it is a rich source of these elements, and the preparation of organic fertilizers from recovered nutrients can reduce environmental degradation. Almost 22% of the global demand for P can be achieved from human urine (Mihelcic et al., 2011). Thus, the transformation of urine to fertilizers is a win-win system of reusing, recycling, and waste management more sustainably. Stored urine is exposed to various methods under specific conditions for the recovery of different nutrients (Fig. 4).

7.1. Nitrogen

Nitrogen can be recovered from human urine indirectly by converting urea into ammonia upon the addition of NaOH or $Ca(OH)_2$ in urine at higher pH (10) (Chipako and Randall, 2020). Ammonia stripping by making urine acidic and then lowering back its pH is a better method (Wei et al., 2018; Xu et al., 2018). Though its efficiency is only 28%, biological nitrification with distillation is used for the recovery process (Udert and Wachter, 2012). A hydrophobic gas separation membrane system has been used for ammonia recovery with an efficiency of 85% (Nagy et al., 2019). A recovery rate of 90% for NH_3 from hydrolyzed human urine by reverse osmosis and nano-filtration has been reported by Ray et al. (2020). It can also be extracted by struvite crystallization.

7.2. Phosphorous

Struvite crystallization is a potential phosphorus recovery technique. It is the most promising and efficient technique among many other process combinations for the purpose (Lahav et al., 2013; Rahman et al., 2014). This process involves the generation of struvite crystals by adding Mg^{2+} ions to raw waste at pH 8. Nucleation and crystal growth are two steps in this process that leads to the generation and development of struvite crystals. Nucleation is when Mg^{2+}, $NH_4^{+,}$ and PO_4^{3-} meet and form a nucleus for the crystal. Then, ions in solution begin to deposit on the nucleus and the crystal grows in size. The developed bigger-sized struvite crystal is settled and then removed for recovering P from the substrate. Struvite is a phosphate mineral ($MgNH_4PO_4{\cdot}6H_2O$) which is a white to yellowish mica-like crystal and a slow-release fertilizer enriched with magnesium, ammonium, and phosphate (Uysal and Kuru, 2013). The use of struvite as fertilizer is a much better option than synthetic chemical fertilizers (Prabhu and Mutnuri, 2014). The recovered struvite is heated directly in alkali solutions for removing left-over ammonium and hence helps in pollutant removal. Struvite can remove tetracycline (Başakçilardan-Kabakci et al., 2007), entrap and rapidly remove TiO_2 (Blumberg et al., 2009) adsorb dyes on its surface (Foletto et al., 2012) due to its large surface area. It acts as an exceptional host for radioactive cesium (Wagh et al., 2016).

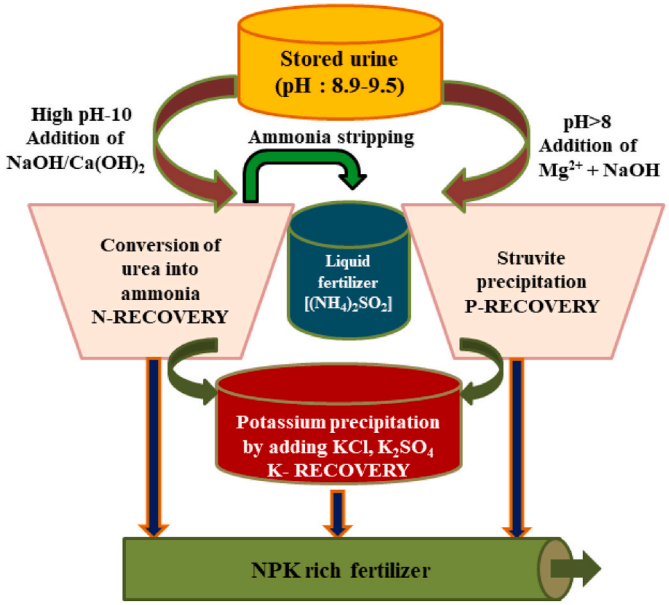

Fig. 4. Various methods for nutrient recovery from human urine in MFC.

7.3. Potassium

Potassium can be recovered from N and P depleted urine by precipitation through potash (KCl, K_2SO_4). Mostly, N and K are recovered in an integrated system that starts with struvite precipitation (Alemayehu et al., 2020). By adjusting pH and temperature, the struvite can be advanced to K-struvite and Na-struvite to include K and Na as part of the recovered fertilizer (Randall and Naidoo, 2018). Potassium can be collectively recovered with phosphorous via precipitation as magnesium K phosphate. Very low concentrations of ammonia and high concentrations of potassium are requisite for efficient K-struvite precipitation, where high nitrogen content in urine is a technical challenge (Bennett et al., 2017). Mostly, K is kept in liquid form and applied as a liquid fertilizer (Udert et al., 2015). Ledezma et al. (2017) recovered 7.18 kg of NH_4^+ $m^{-3}d^{-1}$, 0.52 kg of PO_4 $m^{-3}d^{-1,}$ and 1.62 kg of K^+ $m^{-3}d^{-1}$ treating urine in MFC with anaerobic conditions in the chamber. Very limited literature on recovery of only potassium as a key resource from urine is available currently.

8. Contribution of HU-fed MFCs in meeting city's waste disposal and electricity demand

Recovery of nutrients and production of fertilizers from human urine provides the benefits of curtailing nutrient load in wastewater treatment plants, meeting the city's waste disposal and energy crisis, and contributing to sustainable resource management from waste stream (Ren and Umble, 2016; Tong and Elimelech, 2016). Highly pure ammonia and hydrogen gas are recuperated as added-value products against the cost of treatment (Amanda et al., 2015). Over synthetic fertilizers, farmers prefer the purchase of cheap urine-derived fertilizers (Danso et al., 2017; Jagtap and Boyer, 2020). Electrical energy generation through MFCs is a renewable, economical, and sustainable approach for fulfilling the electrical demand of cities (Salgado, 2009; ElMekawy et al., 2017). Ieropoulos et al. (2013b) were the first to charge mobile phone batteries by MFCs feeding on urine. In a musical festival at the Glastonbury (England) held in 2016, a stack of 12 urine-fed MFCs was used for efficient pee power generation in a decentralized field. COD was reduced by 48%, total nitrogen by 13%, and power output reached 600 mW (Walter et al., 2018). In another case, the pee power project was installed in Sesame Girls School, Nairobi, Kenya, situated in slum areas, the electricity was supplied to LED lights of central corridors of toilet block illuminating two rows of seven cubicles (Ieropoulos et al., 2019). Walter et al. (2020) used a cascade of four membrane-less MFC modules that produced an average of 62 mA at 2550 mV (158 mW) and used that to power a microcomputer. No other power source or electronic circuitry was employed.

9. Recent developments compared to conventional studies

Human urine has generated considerable interest in the field of

wastewater treatment, especially in the past 8–9 years. The first paper published was from Ieropoulos et al. (2012) who described a method for creating electricity straight from pee in MFC, and they were the first to show that pee may be a plentiful fuel for power generation. This had a huge impact on individuals as a paradigm change in how they think about garbage. Advancements were made with passing years in this technology. For instance, Santoro et al. (2013) used membraneless MFC design for electricity generation, Ieropoulos et al. (2013a) used miniaturized and stacked MFC design with terracotta separator for producing power for mobile phone charging, You et al. (2014) used modified carbon-veil anodes for enhanced performance of MFCs in terms of bioelectricity generation, Walter et al. (2016b) used self-stratifying membraneless MFCs for high power output. In recent times, many developments have been made in this technology for achieving higher power output and maximum resource recovery. Different types of electrode materials are used, different types of separating membranes are investigated and even MFCs without membrane are used, use of different binders and catalysts, scaling and stacking, double-chambered and tubular MFCs, the addition of sea salts, optimization of experimental conditions for the development of electroactive biofilms are the recent developments in this study. For instance, Gajda et al. (2020) used a small-scale, low-cost ceramic-membrane-based MFC that converts human urine into electricity while generating a clean catholyte into an originally empty cathode chamber via electro-osmotic drag. It is the first time that catholyte is formed as a by-product of urine with simultaneous electricity generation. Therefore, the increasing number of novel manuscripts published demonstrates an expanding research field and new developments with each passing day.

10. Future recommendations

Different types of MFCs are currently used yet they are limited in terms of industrial scalability, monetary costs, and universal applicability due to their critical development phase. Though MFCs have shown impressive developments in recent times majority of the best performing MFCs studied to date have been constructed at laboratory scale under organized conditions. Studies need to be performed in the field before the successful implementation of this technology in the real-time world. The understanding regarding the microbial reactions that occur in the system and are responsible for the current generation is still in the initial stages. So, research may be carried in this direction for having a clear picture of microbial role in the scale-up MFCs. Application of MFC in robotics, and utilizing valuable recovered resources are the indicators for future hope towards the commercialization of these systems. Currently, there is limited literature available on applications of recovered struvite, the majority of which is focused on soil fertility when used as a fertilizer. Research is further required to optimize the effective nutrient recovery methods more accurately. Studies on K recovery from human urine in solid form are scarce, and thus provide broad opportunities for future research. For technology implementation in the future, long-term stability over many years, high efficiency using cost-effective materials, and an increase in electricity production are very promising in helping the technology enter the wider market. Further work is required to properly understand the mechanism of binders as well as new options that could be added to the shortlist of the binders that are currently used in MFC cathode.

11. Conclusion

Sanitation has been neglected for a long time and the continued failure of international schema to address this aspect has considerably affected global health. Therefore, improving sanitation is vital. On these lines, MFCs fuelled with human urine are an interesting option. Direct electricity generation, saving energy due to anaerobic treatment, low sludge yield, the higher conversion rate of chemical energy into electric current, a broad range of operating temperature conditions (20–40 °C), water reclamation, low carbon footprint, no external source of electricity required for aeration, value-added products recovery, and amenable to environmental stress are some unique advantages that make MFCs preferable than other conventional technologies. The in-situ generation of a bacterial killing agent (catholyte) from urine, NPK enriched organic fertilizers, and struvite offers great opportunities for practical implementations in thematic areas of wastewater management, water reclamation, and reuse, and resource recovery. The electricity output of a single MFC unit is relatively low, so it is necessary to scale up multiple units to gain high energy density for practical implementation in the real world and maximize resource generation. However, scale-up remains a challenge because of the high cost of catalysts and commercial proton exchange separators used in scaling. On these lines, ceramic membranes can be a good alternative to expensive membranes ascribed to their low cost and low maintenance requirements. Small and medium height of electrodes shows higher power output and lesser power density losses. Low-cost membrane materials with high proton conductivity or certain porous materials with comparable efficiency can be used as a separator in MFCs. Electrodes modified with nanoparticles have the potential of producing electricity manifold than plain electrodes. The electricity production rate of MFCs can be enhanced by modification of certain aspects like electrode materials, their surface area, inoculum architecture, electrolytes, catalyst and enzyme coating, the polymer used for binders, bacteria species, and optimization of operational parameters and external resistance. Polytetrafluoroethylene (PTFE), nafion, and chitosan-based materials are the most extensively used binders to fix an active layer onto an electrode support material.

Credit author statement

Rozi Sharma: Writing – original draft preparation, Writing – review & editing, **Rekha Kumari:** Writing – original draft preparation, **Deepak Pant:** Writing – review & editing, **Piyush Malaviya:** Conceptualization, Resources, Methodology, Writing – original draft preparation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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